Quantum Measurement as Irreversible Interaction Events

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Abstract

The quantum measurement problem arises from a structural asymmetry in standard formulations of quantum mechanics: while unitary evolution is treated as fundamental, irreversible events are introduced only through ad hoc postulates. As a result, measurement, decoherence, and probability appear conceptually disconnected. In this work, we propose a minimal reformulation in which irreversible interaction events are taken as ontological primitives. An event is defined as a completely positive, trace-preserving map that is not equivalent to any unitary transformation. Unitary evolution emerges as an effective description valid between events. Within this framework, quantum measurement is not a special process but a particular class of irreversible events with outcome-resolving structure. The Born rule arises naturally from the statistical structure of event realizations, and environmental decoherence is reinterpreted as a high density of irreversible events. No collapse postulate, observer-dependent rule, or modification of quantum dynamics is required. This formulation provides a unified and physically grounded resolution of the measurement problem and establishes a conceptual foundation for event-based extensions connecting quantum theory with spacetime and gravity.

1 Introduction

Since its inception, quantum mechanics has been remarkably successful as a predictive framework, yet its conceptual foundations remain unsettled. Central among these difficulties is the measurement problem: the apparent incompatibility between continuous unitary evolution and the discontinuous appearance of definite outcomes.

In the standard formulation, quantum systems evolve according to the Schrödinger equation until a measurement occurs, at which point a non-unitary projection is postulated. This division between ordinary dynamics and measurement is not derived from the theory itself and has motivated numerous interpretational and dynamical proposals.

Prominent responses include the Copenhagen interpretation, which accepts the division as fundamental but leaves its boundary vague; many-worlds approaches, which deny collapse at the cost of proliferating unobservable branches; decoherence-based accounts, which explain suppression of interference but not outcome selection; and objective collapse models, which introduce new stochastic dynamics.

Despite their differences, these approaches share a common feature: irreversible events are not treated as fundamental physical entities. Instead, irreversibility is either postponed to the level of observation, relegated to effective descriptions, or imposed through additional postulates.

In this paper, we argue that the measurement problem originates from this omission. We propose a minimal reformulation of quantum mechanics in which irreversible interaction events are taken as primitive. Measurement, decoherence, and probability then emerge as natural consequences of event structure rather than as independent axioms.

2 Irreversible Interaction Events as Primitives

2.1 Definition of an event

We define an *irreversible interaction event* (hereafter simply an *event*) as a completely positive, trace-preserving (CPTP) map

$$\Phi : \mathcal{D}(\mathcal{H}) \to \mathcal{D}(\mathcal{H}), \tag{1}$$

that is not equivalent to any unitary transformation and admits no inverse that is itself completely positive.

Physically, an event represents an interaction in which information is irreversibly transformed or discarded. Unlike unitary evolution, an event cannot be undone even in principle. This irreversibility is taken as an intrinsic property of the interaction, not as a consequence of coarse-graining or ignorance.

2.2 Unitary evolution as an effective description

Between events, quantum systems undergo reversible propagation described by unitary operators. Such evolution preserves entropy and information content. However, by itself it generates no physical occurrence: it merely transports and correlates existing information.

In the present formulation, unitary dynamics is not fundamental but effective. It describes the propagation of quantum states between events, while events themselves constitute the physical occurrences that define change.

This inversion of priority—treating events as fundamental and unitary evolution as secondary—forms the core conceptual shift of the present work.

3 Measurement as a Special Class of Events

3.1 Measurement interactions

A measurement interaction is an event with a specific internal structure that correlates a system with a set of macroscopically distinguishable outcomes. Formally, such an event admits a Kraus decomposition

$$\Phi(\rho) = \sum_k M_k, \rho, M_k^\dagger, \tag{2}$$

where the operators M_k correspond to mutually exclusive outcomes.

No additional postulate is required to select an outcome. The realization of a specific Kraus branch is the physical occurrence of the event itself.

3.2 Outcome definiteness

Outcome definiteness arises from irreversibility. Once an event occurs, the system cannot be returned to a coherent superposition of alternative outcomes without introducing new interactions. The exclusivity of outcomes is therefore a direct consequence of the non-invertibility of events, not of any subjective act of observation.

3.3 Absence of collapse postulate

What is traditionally called wavefunction collapse is, in this framework, simply the occurrence of an event. The language of collapse reflects an attempt to describe an irreversible physical process using a formalism designed for reversible dynamics. By treating events as primitive, the collapse postulate becomes unnecessary.

4 Origin of Probability

4.1 Event statistics

The probabilistic character of quantum measurement arises from the statistical structure of event realizations. For a given event with Kraus operators M_k, the probability of realizing outcome k is given by

$$p_k = \mathrm{Tr}(M_k^\dagger M_k, \rho), \tag{3}$$

which follows directly from the structure of completely positive maps.

Probability is therefore not an additional axiom but a measure of how frequently different irreversible transformations occur when an event is repeated under identical conditions.

4.2 Relation to the Born rule

The Born rule appears here not as a postulate about measurement but as a statistical consequence of event structure. This interpretation shifts probability from an epistemic concept to an objective feature of physical interactions.

5 Decoherence Reinterpreted

5.1 Environmental interactions

Environmental decoherence is commonly described as the result of entanglement with unobserved degrees of freedom. In the present framework, the environment acts as a source of frequent irreversible events.

As the density of events increases, coherence between alternative branches is rapidly suppressed. Decoherence thus reflects the cumulative effect of many irreversible interactions rather than entanglement alone.

5.2 Lindblad dynamics

The Lindblad master equation provides an effective description of the average influence of events distributed in time. It is naturally interpreted as a coarse-grained representation of underlying discrete events rather than as a fundamental law.

6 Relation to Other Interpretations

6.1 Copenhagen interpretation

The present framework removes the need for a privileged role of measurement or observer. Events are physical processes occurring independently of observation.

6.2 Many-worlds approaches

Many-worlds formulations retain global unitarity and interpret branching as a formal decomposition of the wavefunction. In contrast, the present approach treats branching as a real, irreversible physical process.

6.3 Relational and subjective interpretations

Relational and Bayesian interpretations emphasize the role of information and belief. While compatible at an operational level, the present framework maintains an objective ontology of events.

7 Discussion

By elevating irreversible interaction events to fundamental status, the measurement problem is resolved at its root. Measurement, decoherence, and probability are unified as aspects of event structure rather than as independent principles.

This reformulation does not modify the mathematical formalism of quantum mechanics but reorders its conceptual foundations. The approach naturally accommodates extensions in which event density depends on spacetime structure, providing a bridge to gravitational and temporal phenomena addressed elsewhere.

8 Conclusion

We have proposed an event-based reformulation of quantum mechanics in which irreversible interaction events are treated as primitive. Within this framework, quantum measurement is no longer a special or problematic process but a particular instance of an irreversible event. Probability and decoherence emerge from the statistical and dynamical properties of events, eliminating the need for collapse postulates or observer-dependent rules. This perspective provides a coherent and physically grounded resolution of the measurement problem and establishes a foundation for further developments connecting quantum theory with spacetime and gravity.

References

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